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Determination of a Worst-Case Acceptor for Large-Scale Sympathetic Detonation Testing

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13. ABSTRACT *(Maximum 200 words)*

The Project Manager for Ammunition Logistics (PM-AMMOLOG) has an interest in barriers which prevent sympathetic detonation between large stacks of ammunition. Tests of such devices are very expensive, and the results are valid only for the munitions that are tested. To extend the validity of such tests, PM-AMMOLOG would like to identify "worst-case acceptors" which can be used in such tests. A successful test with a worst-case acceptor would validate a barrier concept for a much larger class of ammunition. To identify these acceptors, we have subjected selected ammunition items to double-shock and crushing tests. Of those items tested, a thin-walled composition B charge was most susceptible to these stimuli.

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PREFACE

On 30 September 1992, the U.S. Army Ballistic Research Laboratory (BRL) was deactivated and subsequently became a part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

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ACKNOWLEDGMENTS

One of the difficulties faced in this project was the selection of potential worst-case ammunition items. An effort was made to include items that represent most kinds of ammunition items. The assistance and comments of several individuals with experience in ammunition was obtained and is appreciated, both in obtaining comprehensive lists of ammunition in the inventory and suggestions as to which of these might be the most sensitive. The persons and organizations supplying the majority of this help were Michael Swisdak (Naval Surface Warfare Center), James Tancreto (Naval Civil Engineering Laboratory), Clifford Doyle (U.S. Army Technical Center for Explosive Safety), Jerry Ward (DDESB), and the AMC Field Safety Agency.

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1. BACKGROUND

The Safeload Program in the Office of the Project Manager for Ammunition Logistics (PM-AMMOLOG) has sponsored a large number of tasks designed to improve the safety of operations involving ammunition in the logistics chain. An example is the development of sand grid walls to be placed between trucks uploaded with ammunition, allowing the trucks to be parked close together while preventing the communication of reaction between trucks, given an explosive event on one truck. Generally, these tasks have been application specific. But while they have been approved for use after successful testing, approval has been limited to the ammunition tested and the test scenario. With the approval of the Department of Defense Explosive Safety Board (DDESB), it was decided to increase the range of application of safety designs and techniques developed by determining which ammunition item(s) in the inventory were most susceptible to sympathetic detonation. If such an item can be demonstrated to be the most sensitive to sympathetic detonation, then devices and concepts shown to prevent sympathetic detonation with these "worst-case acceptors" (WCA) should have applications for items known to be less sensitive. In addition to increasing the range of application, there are substantial savings in test dollars. Based on this concept, a program was initiated and funded to determine the WCA from the many ammunition items in the inventory.

This task was more difficult than it first appeared. There are a large number of potential candidates in the U.S. Army inventory—the U.S. Army Defense Ammunition Center and School (USADACS) handbook lists 566 hazard class 1.1 munitions. Furthermore, hazard class 1.3 items cannot be excluded because some are detonable when loaded over large areas. In an experiment at the Army Research Laboratory (ARL), a square M30 propellant bed 30 cm wide × 30 cm long × 5 cm deep was loaded by a brass flyer plate, moving at 470 m/s. The reaction which occurred produced pressures close to those expected from detonation. Hazard class 1.2 presents only a fragment threat and hazard class 1.4 only a moderate fire threat and were not considered appropriate for this study.

Another problem is that the ordering of explosive sensitivities can depend upon the details of the test. For example, a comparison of Composition B and RX-08-EL shows a critical buffer thickness of 51 mm and 70 mm, respectively, in the U.S. Naval Ordnance Laboratory (NOL) large-scale gap test. However, in critical buffer thickness tests in 105-mm M1 projectile hardware, the critical thicknesses were 9.6 mm for Composition B and 0 mm for the RX-08-EL.[1] Reversals such as this show that different mechanisms can be operative in sympathetic detonation tests, and the order of sensitivity depends on which mechanism is operative. As a result, it is necessary to give careful consideration to the kinds of tests required and the details of the experiment. This report describes the approach to this problem.

2. OBJECTIVE

The goal of this effort is to determine through tests, guided by computational efforts, which ammunition item(s) are the worst-case acceptors. Cost constraints limit testing to single items, so tests must be designed to simulate the kinds of trauma an ammunition item would experience in the scenarios of concern to PM-AMMOLOG.

3. APPROACH

To make this task manageable, it is necessary to first determine what mechanisms of initiation are possible; select the kinds of ammunition items to test (from all the many items in the inventory); pick a reasonable number to test that will include representative items of each kind; and lastly, determine the kinds of tests required to achieve the desired goal with maximum confidence. The remainder of this section describes how this was accomplished.

3.1 Mechanisms. Experimental results obtained over a number of years show that there are several possible mechanisms of sympathetic detonation. This greatly complicates the choice of a worst-case acceptor because what is the worst case for one mechanism may not be the worst case for another. Five possible mechanisms for sympathetic detonation are described as follows.

3.1.1 Shock Initiation Due to Flyer Plate Impact. When the donor and acceptor are close and there is no buffer, shock initiation due to flyer plate impact is the dominant mechanism of detonation. The expanding case of the donor, which has not yet broken into fragments, creates a shock wave in the acceptor. This should cause the explosive fill to detonate. This mechanism may also apply when a buffer is present because the buffer may act like a flyer plate. Shock initiation thresholds are known to depend

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[1] Frey, R., J. Watson, G. Gibbons, D. Collis, and K. Scribner. "Some Results Concerning the Mechanism of Sympathetic Detonation." JANNAF Propulsion Systems Hazards Meeting, San Antonio, TX, 1989.

on shock duration, and it is possible for the relative sensitivity of two explosives to be different depending on the duration of the shock which is considered.

3.1.2 Fragment Impact. When rounds are far apart and there is no buffer, fragment impact is the dominant mechanism. Fragment impact may generate a shock in the acceptor, which causes the fill to detonate. Fragment impacts may also cause nondetonative reactions in acceptors that may later escalate to detonation.

3.1.3 Multiple Shocks. If spaced closely together in time, multiple shocks can produce detonations, even though individually they would not produce detonation. For sensitization to occur, the pressure from the first shock must drop to near ambient before the second shock arrives. Presumably, the first shock causes damage to the explosive (possibly incipient reaction) and the second shock drives the damaged material to detonation. The relative susceptibility of materials to multiple shock processes is different from their relative shock sensitivity in an undamaged condition. In a sympathetic detonation test, there are a number of ways that an acceptor round can be exposed to multiple shocks. One possibility is that the acceptor receives an initial shock from the donor or impact of a buffer and then receives a second shock when it is thrown against a wall or an adjacent acceptor.

3.1.4 Crushing. In large-scale sympathetic detonation tests where acceptor rounds are impacted by the buffer material, crushing is the likely detonation mechanism. If the shock of impact does not cause detonation, the crushing action may. Crushing may involve the extrusion of explosive into cracks in the metal case or squeezing it between metal parts so that the explosive undergoes very high deformations. The rate of deformation is probably at least as important as the total amount of deformation.

3.1.5 Burning to Detonation. Another detonation mechanism to be considered is burning to detonation. Transition to detonation is possible from nondetonative reactions if the round is exposed to overpressures for a long time while burning.

3.2 Candidate Selection. The choice of test items was based principally on three factors: (1) the sensitivity of the explosive fills; (2) the desire to test items that were representative of larger ammunition categories; and (3) the experience of people at ARL and elsewhere, in ammunition response to sympathetic detonation tests. Very large items (greater than 100-lb net explosive weight) were excluded, although the U.S. Navy has performed similar tests with the Mark 82 bomb with H-6 fill. As a measure of sensitivity of explosive fills, gap test data were used. Considerable assistance was received from USATCES, the U.S. Army Armament, Munitions, and Chemical Command (AMCCOM), and the U.S. Army Materiel Command (AMC) Field Safety Agency in identifying the explosive fills and availability of rounds. The most sensitive fill identified was Pentolite used in the M2A3 demolition charge. This is a discontinued item and is now only available in a Composition B fill. Initially, funds were available for testing of six items. Late in the program, funds to test a seventh item became available and the M67 hand grenade was added to the list of ammunition to be tested. The following paragraphs list the items tested with a brief rationale explaining why each was selected.

3.2.1 M107 155-mm Projectile With Composition B Fill. The M107 Composition B-filled 155-mm projectile was selected because it is representative of thick-walled projectiles, and Composition B is more sensitive than the TNT-filled rounds. In one-on-one sympathetic detonation tests, a thick wall is usually protective (i.e., thin-walled munitions usually sympathetically detonate more readily than thick-walled munitions). However, in the situations that we are considering, which involve long duration and high total impulse loads, the heavy confinement may exacerbate the problem. We did not expect that the M107 would be the worst case, but it is representative of a large class of munitions and we felt it should be tested.

3.2.2 M483 155-mm Projectile With A5 Fill. The M483 155-mm projectile was chosen because it contains A5, a sensitive fill containing 98.5% RDX. It represents a class of items containing submunitions. Based on U.S. Navy small-scale gap test results, A5 appears to be the most sensitive main charge fill in U.S. Army use.

3.2.3 Tube-Launched, Optically Tracked, Wire-Guided (TOW) II Rocket Motor. The TOW II rocket motor was selected because it is representative of several minimum smoke, hazard classification 1.1 rocket motors. Its composition is similar (but not identical) to that in the Hellfire missile and to that contemplated for the Line-of-Sight Antitank (LOSAT) system. Wedge test data on propellants of this class indicate that they are reasonable candidates. In addition, as part of the Advanced Survivability Test Bed Program, ARL performed a number of one-on-one sympathetic detonation tests on TOW II motors and found that thick, heavy buffers were required to prevent sympathetic detonation.

3.2.4 M865 LKL-Filled Cartridge and M43 Propellant. Large-caliber gun propellants are usually hazard class 1.3 and are not generally considered a problem with respect to sympathetic detonation.

However, when they are loaded over large areas, hazard class 1.3 gun propellants can be quite sensitive. In one ARL test, a 8.5-mm-thick brass flyer plate traveling at 470 m/s caused a detonation in an M30 propellant bed. There are large quantities of 1.3 gun propellants in the inventory, and it was felt that one of the more sensitive ones should be included in these tests. Recently, LKL propellant has been shown to be unusually sensitive (detonate) in two types of tests (a shaped charge jet impact test and a confined shock propagation test). Therefore, LKL-loaded M865 cartridges were selected for testing. In addition, some generic 105-mm cartridge cases loaded with M43 propellant were also included because this is a new propellant with a high RDX content.

3.2.5 M2A3 Demolition Charge With Composition B Fill. The demolition charge M2A3 was the last item selected for testing. It was selected in the belief that it was available with a pentolite fill and probably was the most sensitive of the items selected. As it turned out, it was only available in a Composition B fill, but it was still included as representative of hazard class 1.1 with extremely light confinement.

3.2.6 M67 Hand Grenade with Composition B Fill. Hand grenades are hazard class 1.1, mass detonating, but differ from other hazard class 1.1 ammunition in that the fuse train is in line and embedded in the explosive charge. Explosives in the fuse train are more sensitive than those in the main charge, and, because they are in line, if they react, they will initiate the main charge. Hand grenades represent a different configuration of hazard class 1.1 ammunition that are potentially quite sensitive and were added to the list of ammunition items to be tested.

4. TEST PHILOSOPHY

Not all the initiation mechanisms described previously were tested. Fragment initiation was not considered because for the scenarios for which these results are appropriate, it is assumed that buffers capable of intercepting threat fragments will be used. Anyone using these results must demonstrate that primary fragments will be stopped before they can impact an acceptor.

Burning to detonation transition under long durations of overpressures is another mechanism that was not tested. A test of initiation by this mechanism is extremely difficult to perform for experimental reasons. It was also determined to be a very expensive test. However, the data collected included reactions which were not detonations where the test item was destroyed by burning. These data points are identified in the results and can be used to estimate if this mechanism is likely to occur, based on the scenario of application.

The remaining three mechanisms were tested in two test configurations described in succeeding text. Because the objective of this test series was to determine the worst-case acceptor, it is not necessary to determine the level of stimulus required for initiation of each ammunition item for each test condition. Therefore, a double-shock test was used to test both for single- and double-shock initiation by discriminating between where the reaction occurred. If it occurred at the point of flyer plate impact, then single shock is the initiation mechanism, but if reaction occurred at the backstop, then initiation is by double impact.

The dimensions of the flyer plate to be used in these tests was a matter of some concern. The flyer plate must be small enough to be readily accelerated to velocities required, without exceeding the explosive limits of the test range. To obtain a pressure of 15 kbar in Composition B by a steel plate impact, a plate velocity of 320 m/s is required. The sound velocity in steel is about 5.8 km/s and in Composition B at 15 kbar is about 3.37 km/s. A minimum thickness for the flyer plate then should be (5.8/3.37)/2 times the radius of the test item. This is about 2.5 in (63 mm) (thicker will give a longer shock duration). Aluminum plates were also considered, but were not used because of cost concerns. The flyer plate thickness of 4 in (100 mm) was chosen because it could be accelerated to the desired velocities without exceeding the explosive limits of the range, and was thick enough to provide reasonable shock durations in the test items. The lateral dimensions of the flyer plate determine the total explosive weight once a velocity and required thickness of explosive are determined. In a compromise decision, it was decided that plates 2.5 to 3 times the test item diameter and 1.2 times the length would be used. The object is to attempt to keep the impulse per unit area on the test items nearly the same. Four sets of flyer plates were used in these tests; the largest (4 in × 18 in × 30 in) were those used for tests on 155-mm projectiles and the smallest (4 in × 6 in × 4 in) were used on the hand grenades. For all tests, the flyer plate was surrounded by a 4-in-thick and 4-in-wide picture frame. By extending the explosive to the edge of the frame, edge effects were eliminated, and the measured velocity of the flyer plate was always very close to the calculated Gurney velocity. The experiments were designed to catch the frame so that it did not participate in the experiment.

The figure of merit used in these tests was flyer plate velocity (i.e., the lower the plate velocity that causes initiation, the more sensitive the test item). No instrumentation to measure internal pressures in the round under test was attempted. The reactions were recorded as follows: no reaction, burn, explosion, or detonation. Few detonations were recorded, and only those where a detonation signature was observed on the witness plate received this designation. If there was any doubt, the result was designated as an explosion. Burns were included in the rankings because scenarios can exist where a burn reaction is unacceptable.

Concurrent with the start of testing, a series of computations was performed to estimate the pressures that the acceptor explosive would experience in a generic cylindrical configuration. Of particular interest was the pressure experienced at the second impact in the double-shock test and the pressure rise time in the crush configuration. HULL code two-dimensional, axisymmetric calculations were made for the crush configuration. The problem was modeled as a cylinder with dimensions to match the M107 projectile with an inert explosive (explosive was not allowed to react). The constitutive properties and material parameters were available in the code library. Two steel plates and two PMMA (Plexiglas/Lucite) plates in alternate layers, with a PMMA layer touching the round, made up the buffer (Figure 1). Station No. 1 was at the explosive/case interface on the side where the buffer contacts the round. The computed pressure-time record for that station is shown in Figure 2. The results shown are for a flyer plate velocity of 300 m/s (984 ft/s). Figure 2 shows that the rise time of the pressure pulse was long, approximately 500 μs, and had a peak pressure of about 700 MPa. These results indicate that the test items will not experience shock initiation in the planned test series, crush configuration.

Calculations modeling the double-impact configuration were made using the CTH code. The M107 projectile was modeled as an axisymmetric cylinder. Initial calculations were made with the flyer plate constrained from following the round after the first impact. Under this condition, the calculated pressures at second impact were quite low and were believed to be unlikely to generate a reaction in the acceptor. Flyer plate velocities of interest were believed to be on the order of 100 m/s (328 ft/s). For this reason, and because it is more likely in the scenarios of application, the remaining computations were made with the flyer plate allowed to follow the round and crush it against the backstop. It is this condition that is shown in the figures that follow. Figures 3–6 show computations of the way the explosive fill is being deformed and the time required for deformation. Figure 7 shows the rapid rise and high pressures obtained at the late stages of deformation.

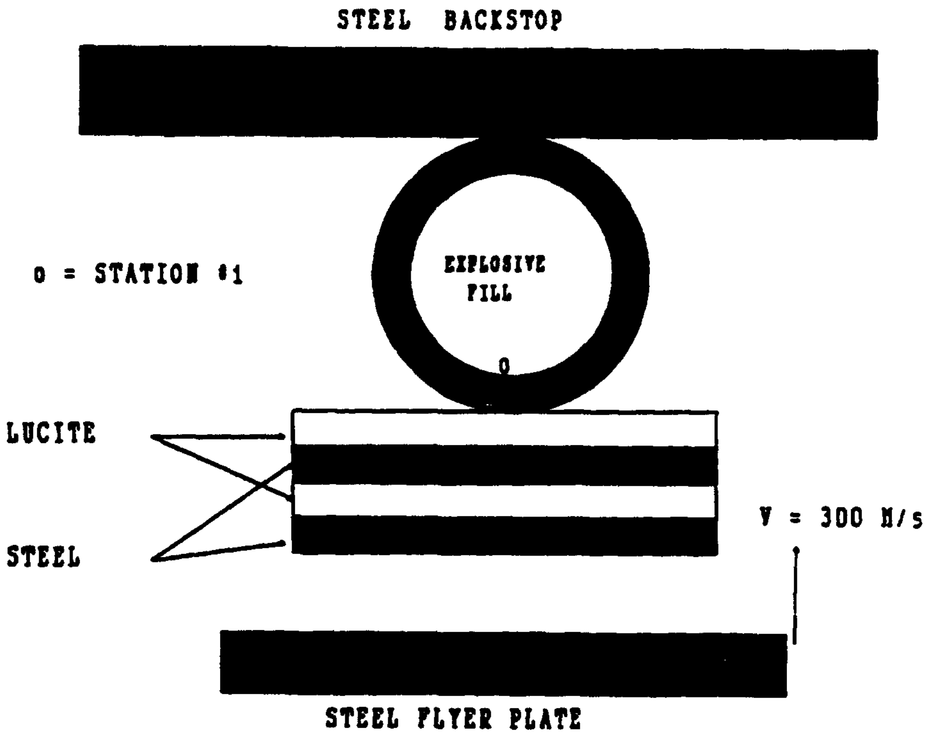

Figure 1. Layout used for calculation of pressures for the crush configuration. (The pressures calculated are shown in Figure 2.)

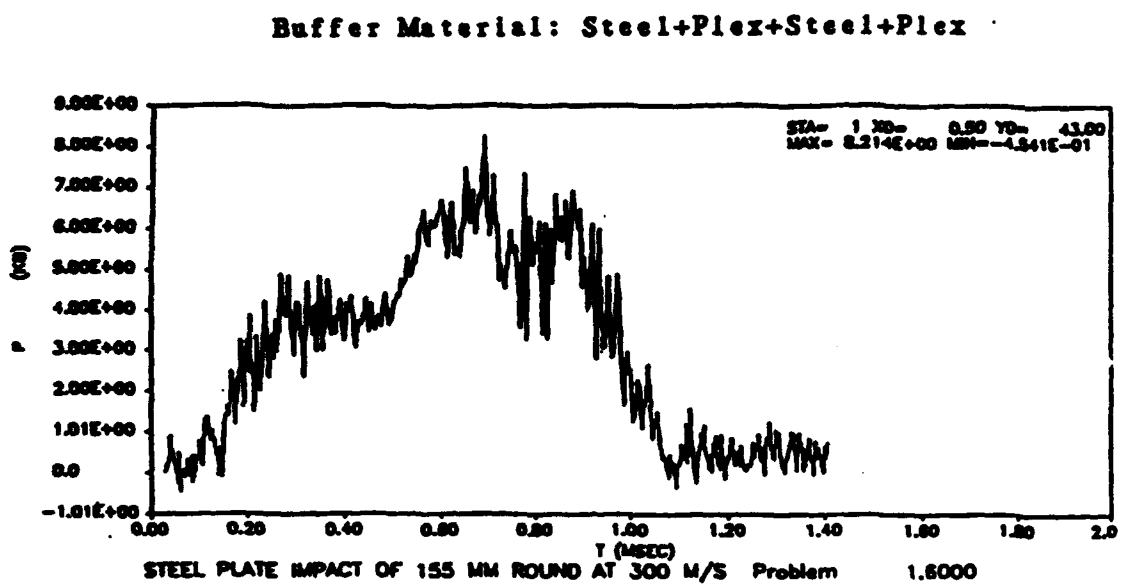

Figure 2. Computed pressure as a function of time for layout in Figure 1 at station No. 1. (Time is in milliseconds; pressure is in kilobars. Plate velocity was 300 m/s.)

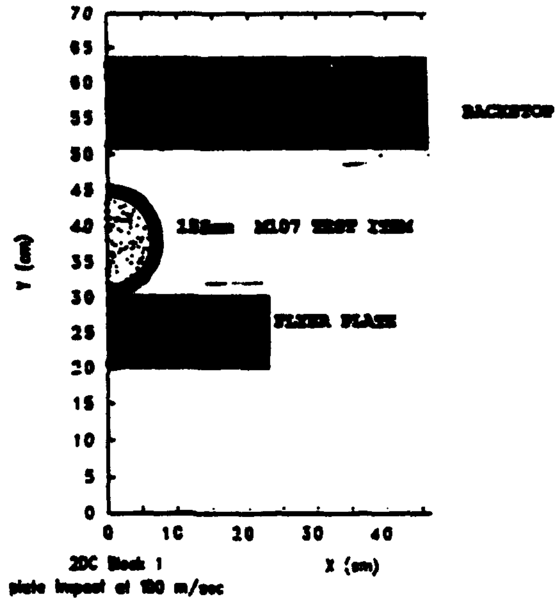

Figure 3. Computer output of deformation resulting from double-impact configuration at 0 m/s.

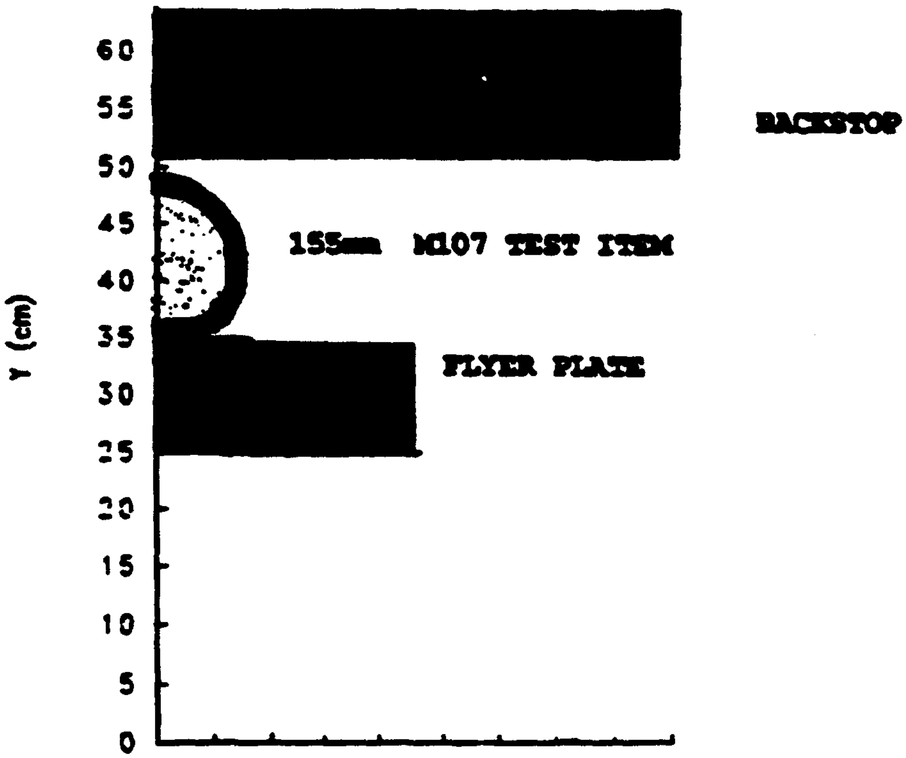

Figure 4. Computer output of deformation resulting from double-impact configuration at 0.5 m/s.

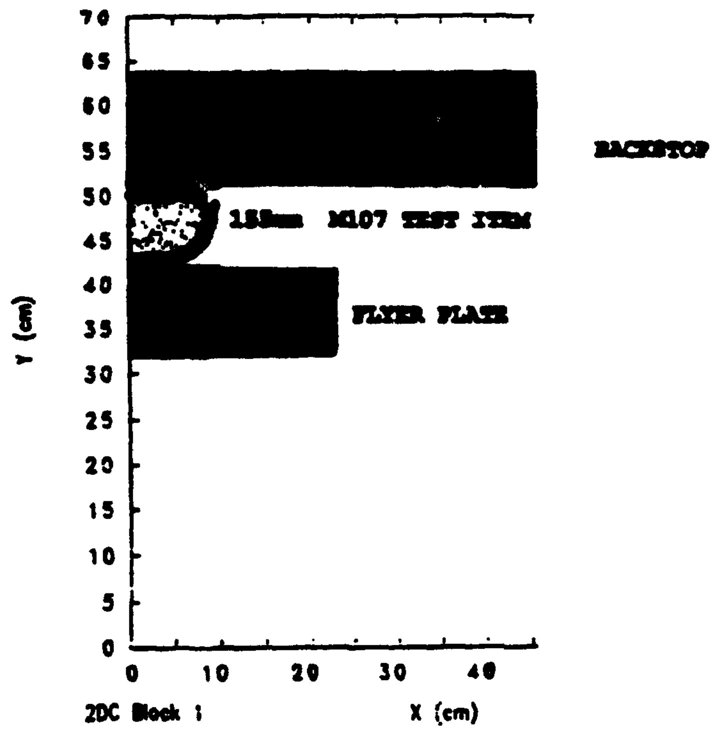

Figure 5. Computer output of deformation resulting from double-impact configuration at 1.3 m/s.

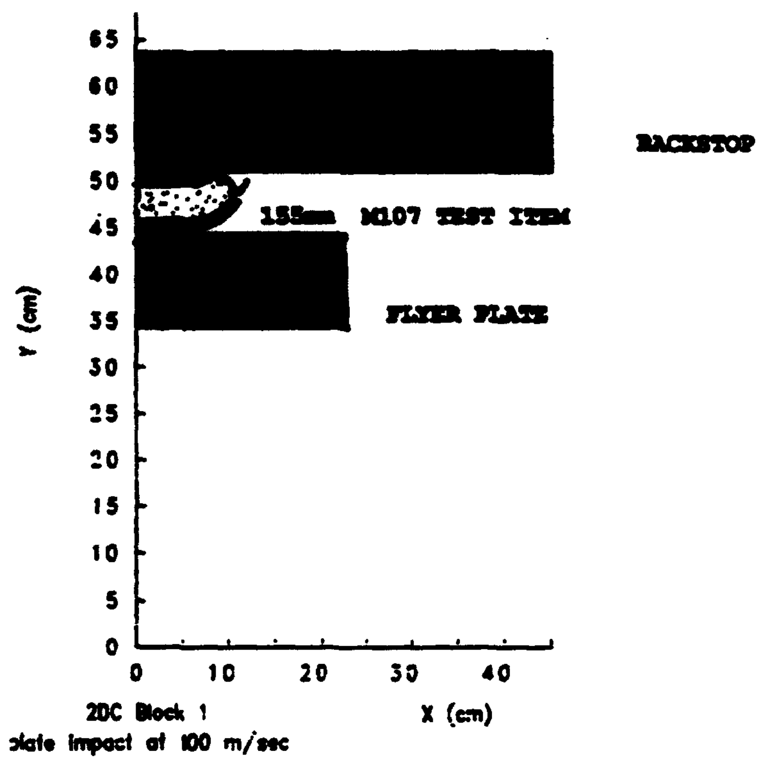

Figure 6. Computer output of deformation resulting from double-impact configuration at 1.6 m/s.

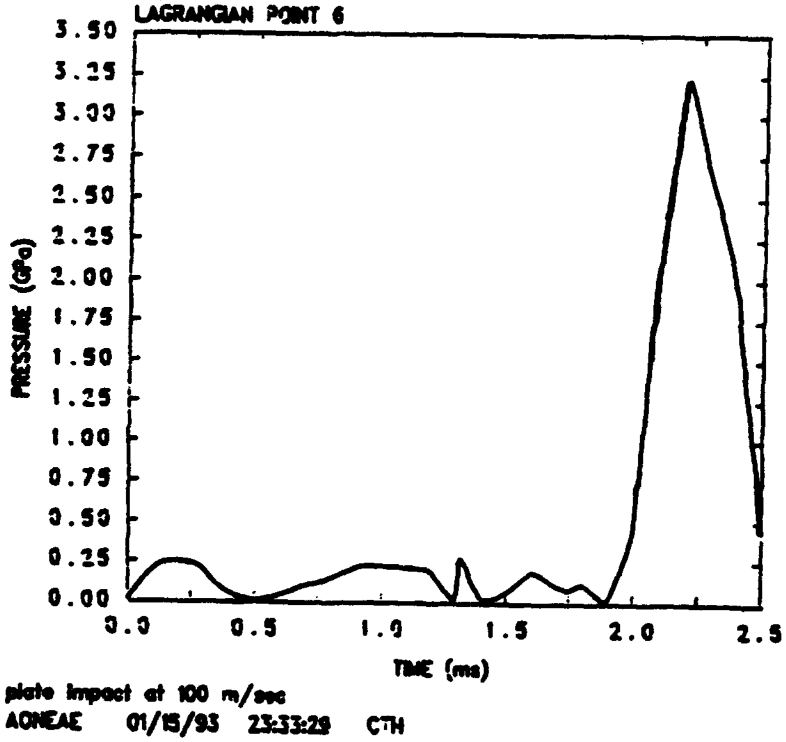

Figure 7. The Pressure (in gigapascals) as a function of time for the test conditions from the previous four figures is presented. (The flyer plate velocity for this calculation was 100 m/s, and the CTH code was the program used.)

5. EXPERIMENTAL SETUP

Two test procedures were used in these experiments. The first was a setup that used a crush package as described in the computations in the previous section. It differed from the design for which calculations were made in that high density polyethylene was used instead of Lucite, and there were four layers each of steel and polyethylene instead of the two layers for which calculations were performed. The double-impact tests were as described in the previous section. Flyer plate thickness was always 100 mm (4 in). Figures 8 and 9 show a plan view of the test setup for the crush test and the double-impact test, respectively. Not shown in Figure 8 is the witness plate, which was a 25-mm-thick (1-in) steel plate placed beneath the munition being tested. This plate allowed the technicians to determine whether the reactions were detonations. Furthermore, the location of the detonation signature was used in the double-impact tests to determine if the detonation occurred at the first impact or occurred at the backstop as the munition was being crushed. In these tests, the tamper plate for the explosive package was only 25 mm (1 in) thick and, consequently, has a larger velocity than the flyer plate; thus it was necessary to install a large barrier to intercept this plate to keep it in the test area. A 1.8-m-square (6-ft) RHA plate 100 mm (4 in) thick was attached to a base of the same size and positioned to intercept the tamper plate. The total weight of these plates with braces was in excess of 5,400 kg (6 tons). The face of this barrier was covered with plywood to reduce the ricochet action.

The flyer plate velocity was controlled by the thickness of the Detasheet used to accelerate it. Detasheet thickness available for these tests started at 1.0 mm and could be increased in increments of 0.5 mm. The flyer plate was surrounded by a frame 100 mm (4 in) wide (the same thickness as the flyer plate) to mitigate edge effects. Flyer plate dimensions were chosen to be about 2.5 times larger in lateral dimension than the test item and about 1.3 times greater in height. The flyer plate travel distance (to impact of test item or crush package) was kept constant for all tests at 100 mm (4 in). Measurement of the velocity of the flyer plate was accomplished with the use of piezoelectric pins. The distance between pins was short, about 25 mm (1 in); in combination with electrical noise problems, this made the accuracy of the velocity measurements somewhat questionable (the time interval was too short compared to the uncertainty in the signal from the pins). To determine how well the actual velocities obtained matched the velocities calculated from the Gurney equations, a series of 1/4- and 1/2-scale tests were performed. The results obtained are presented in Figure 10. The solid curve in Figure 10 is obtained from Gurney calculations for an unsymmetrical slab geometry. The data points are from experiments that measured just the thick plate velocity without the encumbrance of other test purposes (i.e., with a greater distance between pins). Clearly, the data verify the theoretical predictions, and confidence in the velocities measured in tests with target ammunition is justified.

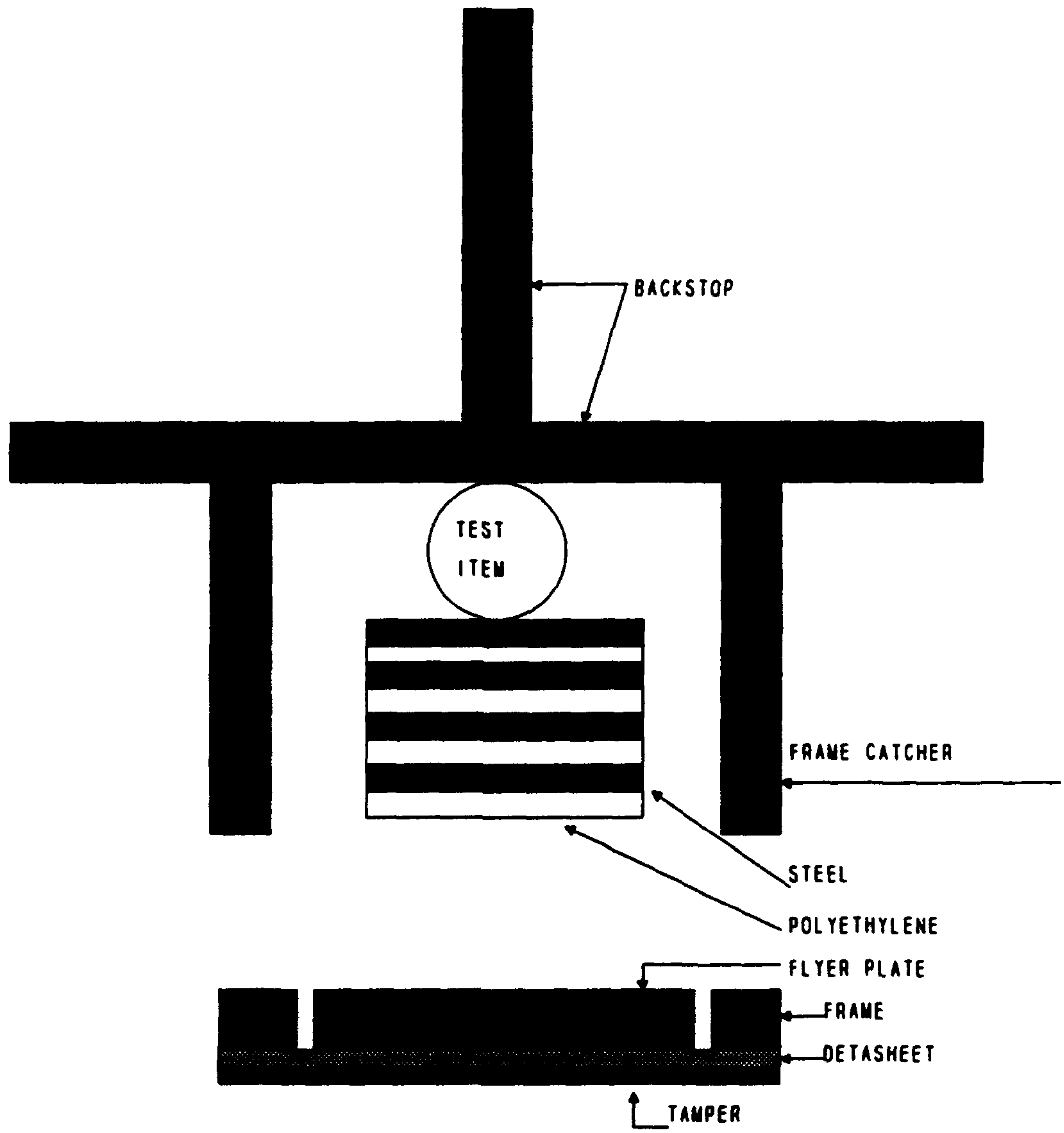

Figure 8. Plan view of the test layout for the crush test configuration.

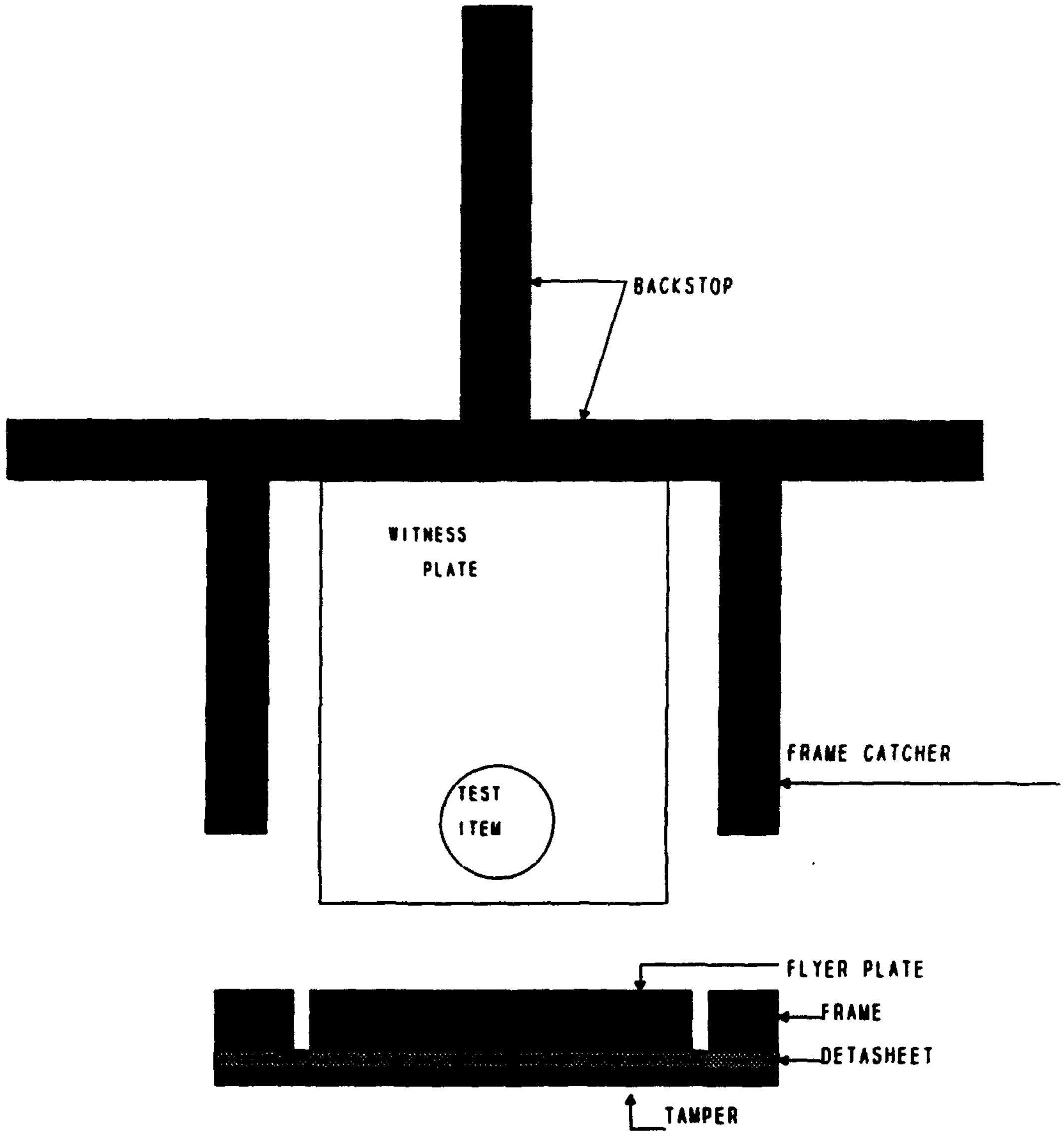

Figure 9. Plan view of the test layout for the double-impact configuration.

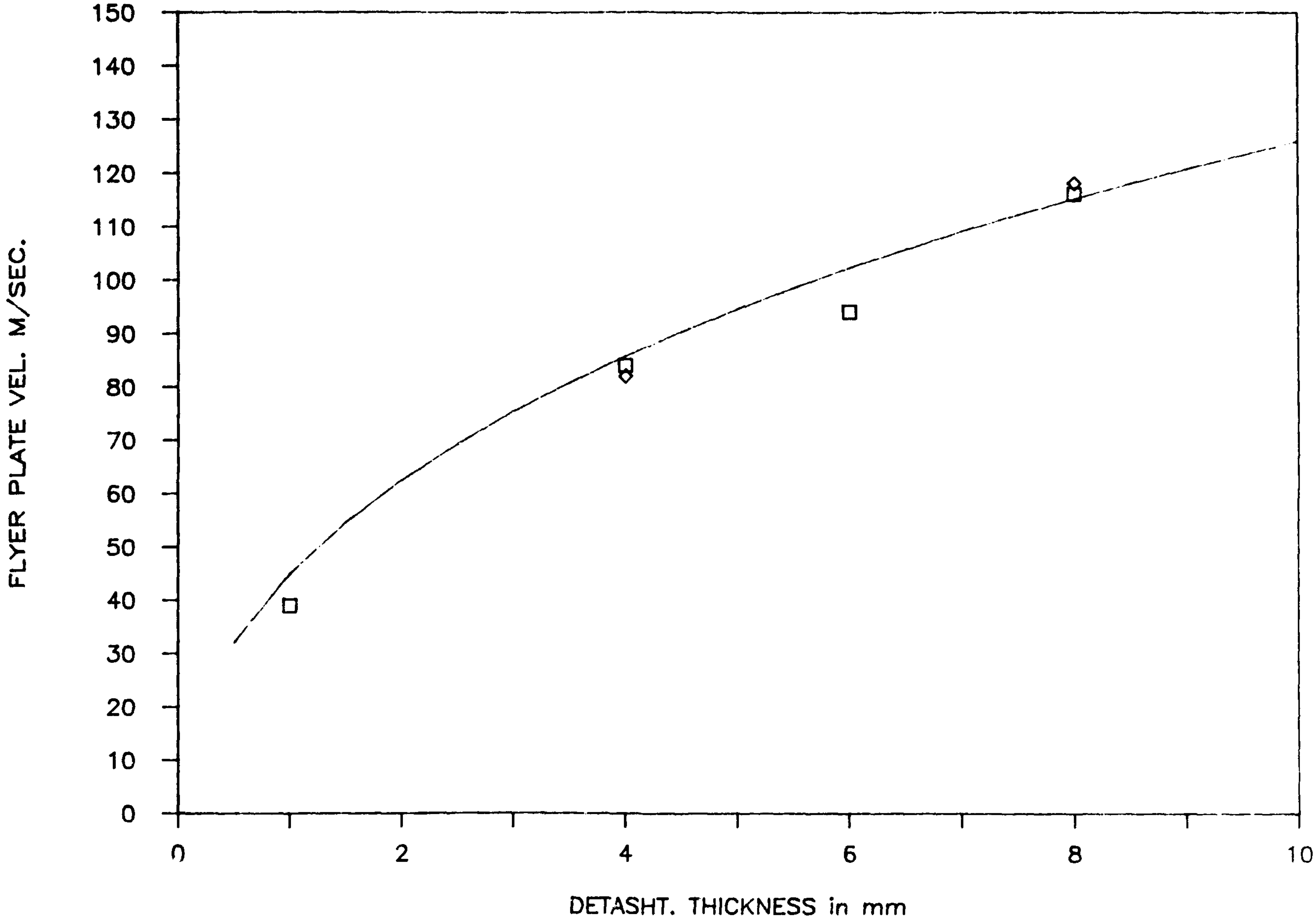

Figure 10. Flyer plate (4-in) velocity vs. Detasheet thickness (for 1-in thickness of steel tamper).

Tests on all the ammunition items except the M107 155-mm projectile and the M483 155-mm submunitioned projectile were conducted at explosive test ranges at ARL's Aberdeen Proving Ground (APG) site. The two munitions not tested on these ranges were tested at the New Mexico Institute of Mining and Technology's (NMIMT) TERA facilities by Mr. David Collis and staff.

6. RESULTS

The results of these experiments are presented in Tables 1 and 2. Table 1 gives the results of the crush tests, and Table 2 gives the results of the double-impact tests. No reactions were observed at the first impact on any of the double-impact tests, indicating that single impact initiation is a less severe trauma, at least under the conditions tested. The tables give a velocity gradient of 10 m/s per cell in the vertical direction, and the test items are listed horizontally. Blank cells indicate that no test was performed at that velocity for that test item. The numbers in each cell indicate measured velocity in meters per second. "Det" means a detonation signature was found on the witness plate, "burn" means the reactive material was consumed by burning, "burn partial" indicates reactive material was recovered after the test, "exp" means a violent reaction occurred, but no detonation signature was found on the witness plate, and "no go" means there was no reaction.

7. CONCLUSIONS

As stated in the objective, the purpose of these tests was to determine the ammunition item most sensitive to sympathetic detonation in communication barrier-type scenarios. Consequently, the exact plate velocity required to produce an explosion or burn of the energetic material was not determined. Such tests were beyond the scope and the budget of this program.

In the double-shock tests, the M2A3 and the hand grenade are clearly the most susceptible to sympathetic initiation. The M2A3 also showed a plate velocity comparable to that obtained for the TOW motor and gun propellants for initiation to burning. Therefore, the M2A3 appears to be the worst-case for sympathetic reaction of the ammunition tested.

Table 1. Crush Test Results

Nominal Plate Speed (m/s)	M67 Hand Grenade	M43 Propellant	M865 Ctg., LKL Fill	TOW II Motor	155-mm M483, A5 Fill	155-mm M107, Comp B Fill	M2A3 Demo. Chg., Comp B Fill
10							
20							
30			30 NO GO	30 NO GO			
40	45 NO GO	45 BURN		45 BURN	43 NO GO		45 BURN
50							
60							
80	86 NO GO	90 BURN	90 BURN	90 BURN	95 EXP	95 NO GO	
100	117 BURN						
120							
140				140 EXP			
160			170 BURN	170 EXP			
180							

Table 2. Double-Impact Test Results

Nominal Plate Speed (m/s)	M67 Hand Grenade	M43 Propellant	M865 Ctg., LKL Fill	TOW II Motor	155-mm M483, A5 Fill	155-mm M107, Comp B Fill	M2A3 Demo. Chg., Comp B Fill
10	14 NO GO						15 NO GO
20							24 EXP
30	30 DET	28 NO GO	35 NO GO	30 BURN (PARTIAL)	33 NO GO		30 EXP
40	45 DET	45 BURN (PARTIAL)		45 BURN (PARTIAL)	49 EXP	47 NO GO	45 DET
50							
60	63 DET						
80							
100	117 DET						
120			125 EXP				
140				140 EXP			
160			170 EXP	170 EXP			
180							

NOTE: Reaction was always at the second impact.

The test design duplicates the kinds of trauma an ammunition item could experience in a logistics environment. The results of these tests indicate that, for the ammunition items tested, the thinly cased demolition charge M2A3 was most susceptible to sympathetic detonation. The case for this munition is a phenolic plastic about 3 mm (0.125 in) thick. The explosive fill was Composition B, which is believed to be more sensitive to conditions of these tests than either C4 or TNT, which are other typical explosive fills for demolition munitions.

Unfortunately, if one is faced with the task of designing a barrier or other device to prevent communication of reaction between ammunition items, it probably will be impossible to predict whether the threat is a double-impact or nonshock crushing. Based on the test results reported here, certainly one would pick the M2A3 demolition charge as a test munition, but it would probably be wise to include a propellant also, either a minimum smoke rocket motor, M43 gun propellant, or both.

The hand grenade results, which were obtained very late in the program, show that it is as likely as the M2A3 to react from the double impact tests. There was no evidence that the fuse played a role in producing a reaction, but neither is there any evidence that rules out this possibility. Because the hand grenade was as sensitive as the M2A3 in double impact tests, one might want to include them in tests of designs to prevent sympathetic detonations, however, they do complicate the tests markedly from a safety standpoint.

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